Aerothermal Analysis of the X-33 Vehicle

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High-fidelity hypersonic acreage aerothermal environments have been computed using state-of-the-art numerical methods for three configurations of the Lockheed-Martin Skunkworks X-33 Phase II vehicle. The aerothermal environments, which include the surface pressures, radiative equilibrium surface temperatures, surface streamlines, and loads, have been computed in two paradigms: (1) a trajectory paradigm in which solutions are computed at several points along design trajectories, and (2) a design space paradigm in which solutions have been computed at several points in a space, parameterized by the free-stream Mach number, angle of attack, and Reynolds number, independent of flight trajectories. These computed aerothermal environments have been used in conjunction with an engineering method to define and design the thermal protection system of the X-33 vehicle. Further, the aerothermal environments for deflected control surfaces (on both the canted and vertical fins of the vehicle) and the effect of yaw have been computed. The effect of configuration changes, an evolutionary process unavoidable in design, has also been studied.

The primary objectives of the work were to integrate high-fidelity numerical methods into the design cycle of the X-33 and to put into place the necessary tools and methods for designing the next generation of reusable launch vehicles (RLVs). During the course of acreage computations of the X-33 aerothermal environments, an attempt was also made to define the aerothermal environment of a 2x-scale X-33 (representative of the RLV) at Mach 25, and to address, in a limited sense, the traceability of the X-33 environment to that of the RLV. The first figure shows, in four views, the comparison of the computed surface isotherms of the X-33 and the RLV at peak heating points on their respective trajectories. The surface is assumed to be fully catalytic with emissivities that are typical of the candidate materials for the thermal protection system. The figure shows that at the peak of the heat pulse during the descent phase, both vehicles experience nearly the same thermal environment, even though the X-33 is at a lower altitude.

The present work clearly establishes the feasibility of integrating high-fidelity numerical methods into the design cycle of hypersonic vehicles, either directly or indirectly, as anchor points for engineering methods. The work also establishes the usefulness of the design space paradigm wherein the aerothermal environment definition is effectively decoupled from the trajectory. Although this approach requires more numerical solutions than the traditional trajectory-based approaches, it speeds up the process of trajectory evaluation and is very useful in studying trajectory dispersions and their influence on the design of the thermal protection system.

The thermal protection system on the windward side of the Lockheed-Martin X-33 technology demonstrator vehicle consists largely of metallic panels. As the vehicle travels through Earth's atmosphere at hypersonic speeds, thermal gradients between the top and bottom face sheets cause the metallic panels to bow. Steps and gaps will exist at the panel/panel and panel/nosecap interfaces. This study used Navier–Stokes flow analysis to assess the effects of the bowing, steps, and gaps on the surface heating of the vehicle. A parametric study was performed at the peak heating: peak Mach, Mach 10 turbulent, and peak negative bowing locations of the Mach 15 trajectory. A series of surface-heating augmentation factors was generated that provides the increase or decrease in heating rate as a function of bow height, step height, and gap width. The existence of reverse flow at the panel interfaces, because of panel bowing, was demonstrated.

The phenomenon of thermal-protection-system panel bowing was also studied in a more rigorous manner. Three numerical models, one for the flow

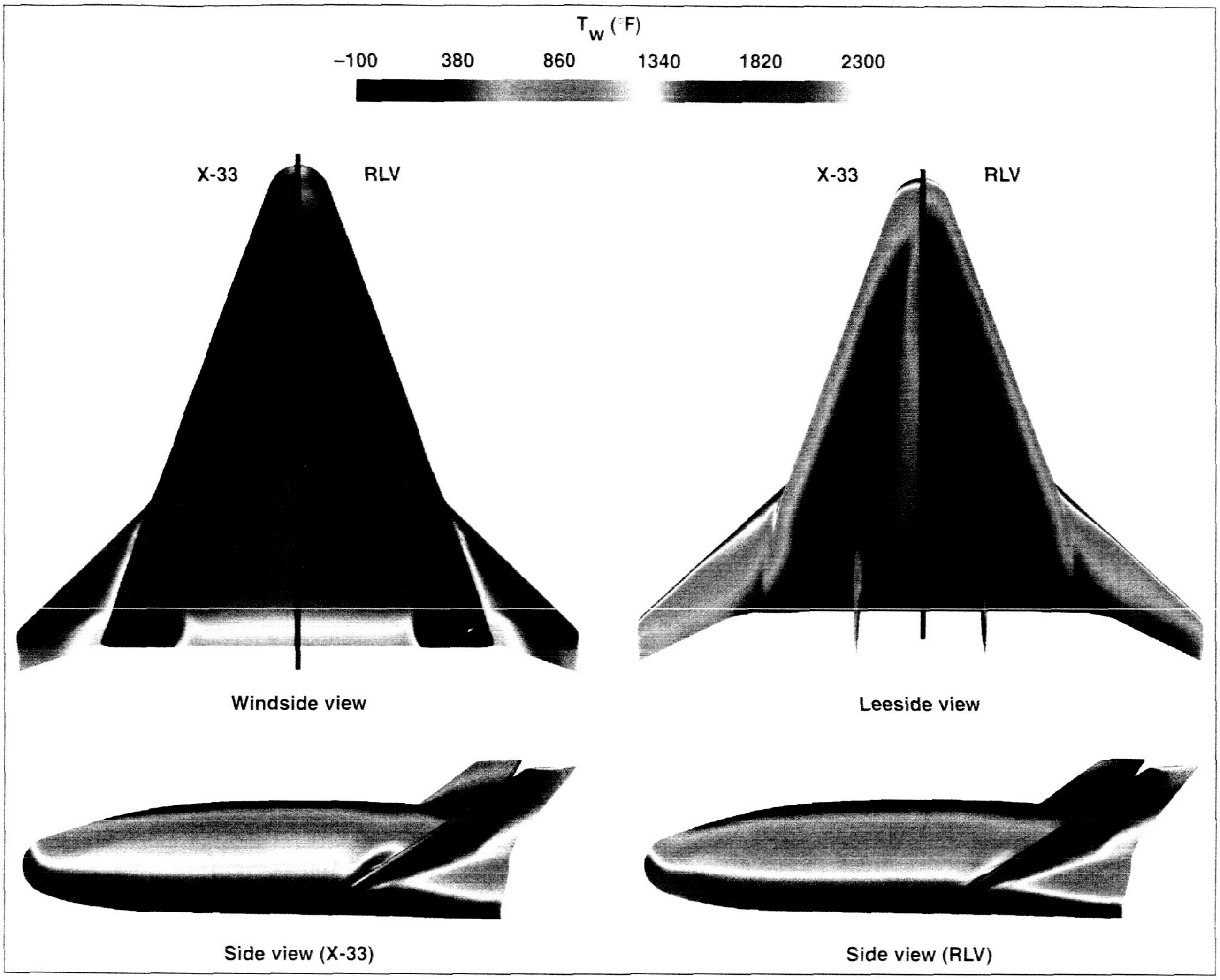

Fig. 1. Comparison of the computed radiative equilibrium surface temperatures.

field, one for the in-depth heat transfer, and one for the thermoelastic deformation, were coupled in sequence to yield the transient response of the metallic panel. The aerothermal loads were derived from computational fluid dynamic solutions and were prescribed as a distribution function with maximum bow height as the governing parameter. Finite-element models were used to simulate the thermal and structural response. The coupled simulation was compared to a single-pass uncoupled solution. Results showed negligible feedback between the structural deformation and the deformation-induced perturbation of the aerothermal heat load. Yet, significant temperature variations were produced on

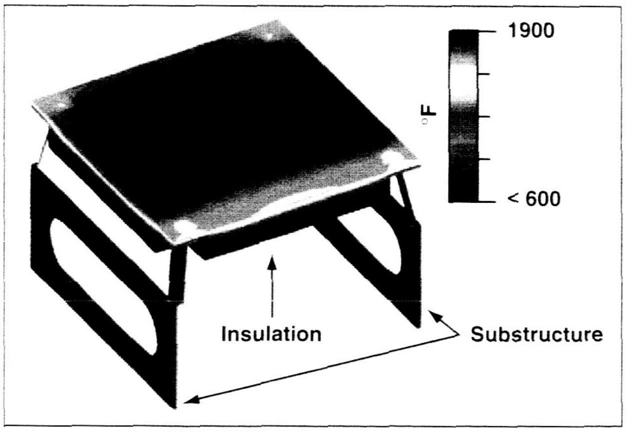

Fig. 2. Surface and in-depth temperatures, peak heating point.

the surface of the panel. The deformations induced lateral temperature gradients that increased the thermal stress within the panel. Finally, it was shown that panel bowing does not appreciably alter the trajectory-integrated heat load. The second figure shows computed surface and in-depth temperatures on a panel/support structure stack-up at the peak heating trajectory point.

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Aerothermal Analysis of the X-34 Vehicle

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The X-34 vehicle will provide the first flight demonstration under NASA's Reusable Launch Vehicle (RLV) program of a fully reusable launch vehicle. Under a fixed-price contract with NASA, Orbital Sciences Corporation (OSC) is to provide a Mach 8 suborbital RLV technology demonstrator. The vehicle is 18.3 meters in length, has a wingspan of 8.4 meters, and is powered by a single LOX-kerosene engine. The X-34 is carried below an L-1011 aircraft to an altitude in excess of 9 kilometers, where the vehicles separate, the X-34 engine starts, and the X-34 vehicle continues along its flight trajectory. The first flight is scheduled for 1999.

Under a cooperative agreement with OSC, Ames Research Center was given the responsibility for designing, analyzing, and fabricating the thermal protection system (TPS) of the X-34 nosecap, wing leading edges, and rudder leading edge. Temperature, pressure, and heating rates on the surface of the X-34 were computed at six points along the X1004701 Mach 8.5 no-bounce trajectory. The work focused on the nosecap, wing/strake leading edges, and the rudder leading edge. These areas are protected from the thermal environments experienced during flight by silicone-impregnated reusable ceramic ablator tiles.

The computational data provided anchor points from which a time history of surface heating and pressure could be generated. This time history will be used to analyze and design the tiles. The figure shows computed surface-temperature contours at the peak heating point on the descent portion of the trajectory. The Navier–Stokes solutions were, when possible, compared with data from engineering correlations.

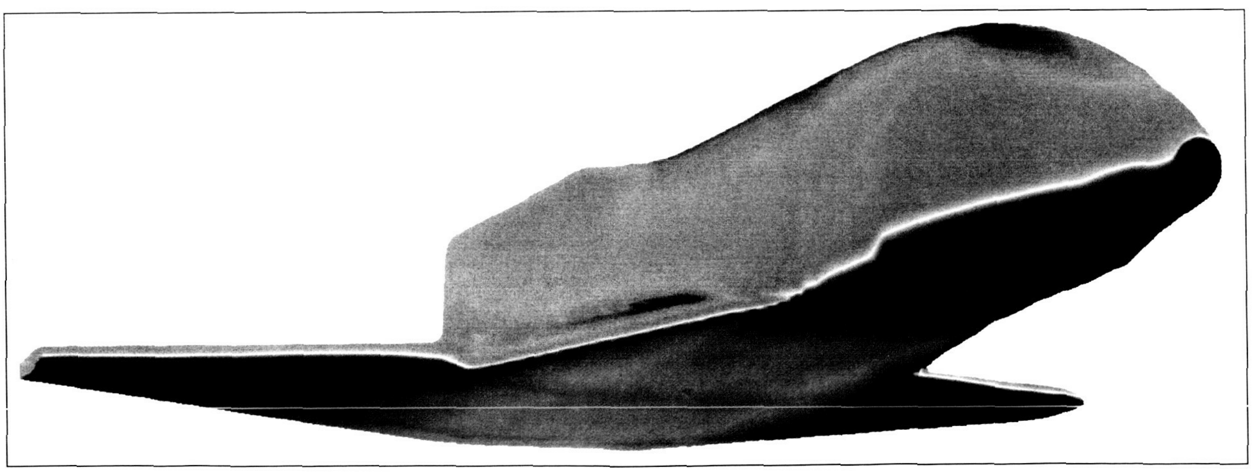

Fig. 1. Surface temperature contours.